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Shannon, Claude (1916-)

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Disciplines
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SHANNON, CLAUDE (1916–)

U.S. mathematician and educator, in the field of communication known largely for his INFORMATION THEORY, which profoundly changed scientific perspectives on human communication and facilitated the concurrent development of new communication technology for the efficient transmission and processing of information. Claude Elwood Shannon's *Mathematical Theory of Communication,* first published as a Bell System Monograph in 1948 and a year later, after insightful review in *Scientific American,* as a book with commentary by WARREN WEAVER, was still in print forty years later. No single book on communication theory has so far surpassed its publication record.

Shannon's ideas did not originate in a vacuum, but none of his predecessors (e.g., Ludwig Boltzmann, Karl Küpfmüller, Harry Nyquist, Ralph V. L. Hartley, Leo Szilard, or Ronald A. Fisher) or contemporaries (e.g., NORBERT WIENER and the independently working Andrei Nikolaevich Kolmogoroff) presented such a large body of coherent concepts, abstract propositions, and theorems, along with a research agenda that could be applied to virtually any discipline concerned with knowledge, and none had the benefit of working at a time or in places so pregnant with intellectual and technological developments in communication. The completeness of Shannon's work (not a single proposition has had to be retracted) and the opportunities it promised for conceptualizing and quantifying a process so basic to human existence surprised many. Within a few years of its publication the theory provided the scientific justification for academic programs in human communication (which sprang up largely in U.S. universities), expanded communication research to new media, created novel areas of inquiry as well as two new journals, and stimulated the development of new communication technology for handling knowledge, including in computers. The theory became a milestone in communication research and marked the transition from an industrial to an information society.

Figure 1. *(Shannon, Claude)* Claude Shannon demonstrating his maze-solving electrical mouse at Bell Laboratories in 1952 in an experiment to study telephone switching systems and the logical powers of computers. Courtesy of AT&T Bell Laboratories.

Born in Gaylord, Michigan, Shannon received a B.S. in electrical engineering from the University of Michigan and an M.S. and a Ph.D. in MATHEMATICS from the Massachussetts Institute of Technology (MIT), where he held the Bowles Fellowship. In 1940, the year he received both graduate degrees, he won a National Research Fellowship at Princeton University. In 1941 he joined Bell Telephone Laboratories as a research mathematician and later became executive consultant to Bell's mathematics and statistics research center. In 1956 he was appointed professor of communication at MIT, where he was given the Donner Chair of Science two years later. He remained a consultant to Bell Laboratories until 1972 and became a professor emeritus in 1979. He has received numerous awards and honorary degrees.

In a nutshell, Shannon's work established novel connections between symbolic and physical forms: Boolean algebra of switching nets, automata theory, cryptography (*see* CRYPTOLOGY), theory of coding (*see* CODE), and, above all, his communication theory (or information theory, as it is now called). Shannon's master's thesis, completed when he was twenty-one, was entitled "A Symbolic Analysis of Relay and Switching Circuits" and was published in 1938. Reputed to be the most important master's thesis of this century, it established an isomorphism between the Boolean logic of propositions and the kind of switching networks then beginning to be used in electronic machines and showed that any logical operation that could be described in a finite number of steps could also be carried out by an appropriate switching circuit. It also suggested that the programming of computers ought to be thought of not as an arithmetical problem (then the dominant view) but as a problem in formal logic. Simultaneously Shannon provided not only a powerful tool for synthesis, analysis, and optimization of relay circuits but also the crucial link between logic—the crown of human reasoning and symbolism—and the newly emerging computing machines. He continued to explore this new synthesis, designing an electronic mouse that could learn from mistakes and find its way through a maze, editing *Automata Studies* with John McCarthy (who became a leading figure in the field of ARTIFICIAL INTELLIGENCE), and pursuing his interest in reliable machines built from unreliable components in work on chess-playing computers, for example.

Shannon's interest in cryptography began as a hobby but took on great significance during World War II, when he became associated with Bell Laboratories, where work on pulse-code modulation was in progress. His confidential monograph *Communication Theory of Secrecy Systems,* circulated in 1945 and cleared for publication in 1949, discussed cryptographic ideals—variable coding transformations that are easy to do and undo and that make the enciphered text seem random—and furnished proofs of the conditions under which cryptograms should in principle be decipherable. The work contained many of the ideas that became central to his information theory. He described communication as "the fundamental problem . . . of reproducing at one point either exactly or approximately a message selected at another point." He showed coding to be central to any communication—a message must be encoded into a medium suitable for transmission and the received signal decoded by applying the inverse of the encoding transformation—and became aware of the need for a statistical characterization of message sources and channels, including transmission errors or noise. Coding problems suddenly came to be recognized as central in research ranging from communication engineering to LINGUISTICS (e.g., in the form of LANGUAGE translation) and resulted in the notion of information processing in humans, machines, or social organizations.

By his own account, Shannon started work on his mathematical theory of communication as early as 1940 while a fellow at Princeton. Subsequent work, especially on coding problems, must have shaped its direction. One of the theory's crucial innovations was its linking of communication to the freedom of choice a sender has in selecting a message, and the constraints this imposes on the receiver. What a message is or contains, why it is selected, or how it is coded became secondary to the choices exhausted in a communication relationship. Realizing that the very idea of communication implies that one cannot know in advance the messages chosen, Shannon decided to regard sending and receiving as a stochastic process, that is, as a process of selecting among sets of alternatives whose probabilities are somewhat dependent and knowable, at least in the long run. For this idea he acknowledged the influence of Wiener's work on statistical prediction and filtering of time series and made use of the Russian mathematician Andrey Andreyevich Markov's 1913 theory of chains of symbols in literature. However, his most consequential invention was the now famous logarithmic measuring function $-\Sigma p_i \log_2 p_i$, for quantifying the volume of choices available, uncertain about, consumed, or channeled. He had misgivings about assigning uncommon meanings to the word *information* and took JOHN VON NEUMANN's suggestion that this function be called *entropy* because its mathematical form resembled one known by that name in quantum physics and interpreted in that field as lack of information. The mathematical properties of this function proved to be unique and enabled Shannon to develop the theory into a full-fledged calculus for information quantities. Shannon avoided the term *information theory* in his own work, suggesting that communication across time and space was always his primary concern.

Although terms such as *freedom of choice, uncertainty, information, information transmission, channel capacity,* (*en-*, *de-*, *re-*)*coding, redundancy, equivocation,* and *noise* quickly spread into many disciplines, they also stimulated wild claims by unqualified enthusiasts who thought they had found a philosophers' stone, and harsh condemnations by equally unqualified critics who supposed an engineering bias, especially in the diagram Shannon used to depict communication processes paradigmatically.

After the early enthusiasm the limitations of Shannon's contribution can now be seen in perspective. First of all, it should be stressed that Shannon contributed a *mathematical theory.* It has a few axioms and an ever-growing number of proven theorems whose rich concepts afford many real-world applications. Like counting, in which it does not matter what one counts as long as the entities concerned are countable, information theory is applicable to any situation in which its axioms can be shown not to be violated. However, applicability does not guarantee meaningful or complete explanations of the phenomena of interest. Because of its content-independent character, information theory has been applied to many areas not directly related to communication: statistics, complexity, memory, intelligence, decision making, uncertainty analysis, self-organization.

Like the concept of energy in physics, which is defined as the capacity for doing mechanical work, information is neither MEANING nor matter but *what a message does* in the context of what is conceived as possible. The theory shifts attention from static attributes of isolated objects to processes of doing logical work in particular contexts—whether these are provided by machines, biological beings, or social organizations.

Like the laws of thermodynamics, the theorems of information theory *assert limits* on what can be done; they do not spell out how to communicate or what to design. Rather, they divide the world into two parts—that which is possible (communicable, controllable, knowable, constructable, etc.) and that which is condemned to remain fiction (like the perpetuum mobile in the physical world). Often these parts are separated by a gap of impracticality.

Like all measurement in science, the information calculus of the theory does not assert facts but enables social scientists to make heretofore unknown *quantitative comparisons* and to pursue research questions posed by the theory's new conceptual apparatus; it also shows engineers where communication resources might be used more efficiently in combating noise with redundancy, designing adaptive computers from unreliable parts, or conceiving simple controllers of complex systems.

After positing his mathematical theory of communication, Shannon worked out missing details, sampling theorems, coding theorems, and the like; invented interesting applications such as his guessing experiments with strings of text, showing that the English language is about 50 percent (later upgraded to 70 percent) redundant; and saw his theory proliferate into numerous disciplines. Despite limitations, which can be found in any theory, Shannon's theory has been neither disproved nor surpassed but has profoundly changed the world of communication.

See also CYBERNETICS; MODELS OF COMMUNICATION.

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